MAGNETIC GRADIOMETRY AND ONGOING MODELING EFFORTS FOR THE *LUNAR VERTEX* MISSION.

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Introduction: The first Payloads and Research Investigations on the Surface of the Moon (PRISM1) delivery targets the Reiner Gamma (RG) swirl and magnetic anomaly [1]. To characterize the magnetic anomaly source and study the potential connection of the associated "mini-magnetosphere" to albedo variations within the swirl, the *Lunar Vertex* (LVx) investigation [2, 3] will carry an array of vector magnetometers on the lander (VML) and an array of vector magnetometers on the rover (VMR). Both instruments were assembled and calibrated at the Johns Hopkins University Applied Physics Laboratory (APL). Measurements during descent recorded by VML and during surface operations by both VML and VMR will characterize the spatial and temporal variation of magnetic fields across the RG swirl (Fig. 1).

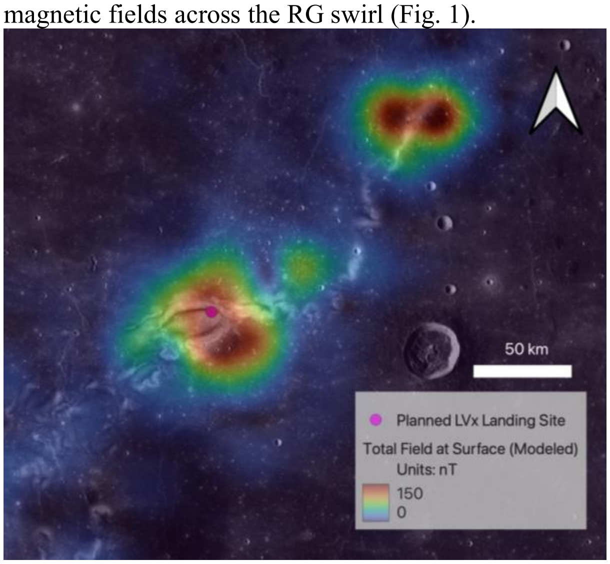

Fig. 1. *Total field modeled at the lunar surface above the Reiner Gamma magnetic anomaly [4], overlayed upon on an LROC WAC monochrome mosaic (100mpp, I/F reflectance image is stretched 0.0245 to 0.0735).*

Using a novel approach in mitigating magnetic field contamination from the lander and rover, VML and VMR observations will place new bounds on the orientation, strength, and depth of the RG magnetic anomaly source. This will provide insight into the formation mechanism of the magnetic anomaly and constrain the formation timeline by incorporating the geologic context of the region. Measuring small-scale variations in the surface magnetic field is also key for understanding the relationship between the magnetic anomaly and the optical swirl pattern [4]. In preparation for the upcoming LVx flight and operations in 2024, we use synthetic data and laboratory data incorporating magnetic sources to determine the accuracy and precision of the VML and VMR gradiometry technique.

Magnetic Gradiometry: VML is comprised of a tetrahedral array of four commercial fluxgate magnetometers mounted on the bottom of a 0.5-meter mast, with a science-grade dual-ring core fluxgate magnetometer mounted at the top of the mast. VML will be located at the top of the Intuitive Machines (IM) Nova-C lander. VMR is comprised of a tetrahedral array of four commercial fluxgate sensors mounted on a 0.2-meter mast, located on the top deck of the Lunar Outpost-provided rover. The tetrahedral array of both VML and VMR is composed of Bartington Mag566 sensors, which are used in a novel form of magnetic gradiometry [5].

The VML and VMR masts are shorter than typical magnetometer mounts, where long (>1 meter) booms are often used to reduce spacecraft-generated fields at the sensor [cf. 6, 7]. Instead, VML and VMR are placed within relatively small "keep-out zones" on top of the lander and rover, respectively, and the relative position of each sensor on the mast is precisely measured. Initial estimates for the location and moment of magnetic sources are derived from gradients between each sensor in the tetrahedral array, and then the estimates are refined through a minimization algorithm.

The output of the minimization algorithm is referred to as the "tetrahedral correction" and is applied to VML and VMR data as part of the calibration process. VML will additionally use an inboard-outboard correction [8] between the Mag566 sensor array and the science-grade APL fluxgate magnetometer, while VMR will use the average corrected vector of the Mag566 sensor array. This is an improvement over previous inboard-outboard noise corrections, which used linear magnetometer arrays mounted on long booms [8, 9]. By identifying sources of magnetic noise and producing a correction to the observed field, the tetrahedral correction algorithm relaxes the requirement for a boom while maintaining data quality, and the tetrahedral array design allows VML and VMR to be mounted on relatively short masts and carried on a commercial rover and lander that were not initially designed for magnetic cleanliness.

Algorithm Implementation: The tetrahedral correction algorithm was validated using both synthetic data and experimental data. Synthetic data was generated using an ideal dipole source and homogeneously magnetized cuboid and spherical noise sources. The location and moment of an ideal dipole source were varied to explore the parameter space and determine the best multidimensional minimization algorithm for the cost function. A simplex algorithm was selected and implemented to efficiently iterate over the parameter space and identify the best-fit source parameters, given the gradient-derived source parameter estimates as a starting point.

The tetrahedral correction algorithm using synthetic data performs quite well, the final estimate is capable of perfectly tracking an ideal dipole source. Introducing noise to the synthetic data degrades algorithm accuracy, as expected, with the final estimates achieving residual errors of <0.1% when recovering the location and moment of a dipole source in an ambient field of noise that is 5% of the total source magnitude. However, noise levels greater than 25% of the total source magnitude prevent the algorithm from converging on the global minimum of the cost function, resulting in final estimates that fail to locate the source within 15° of the true position. The limitations of noise on algorithm accuracy are still being explored using synthetic data, along with the effects of source distance and moment orientation.

Fig. 2. *Experimental setup in the Magnetics Testing Facilities at APL. Four Mag566 sensors are mounted on a VMR mast prototype centered inside 2-meter Helmholtz coils on a nonmagnetic table. A solenoid thruster actuator is mounted on a tripod to generate a dipole-like thruster signal similar to that which may be observed in flight as the lander maneuvers during cruise and descent.*

Experimental data was generated using approximate dipole sources such as a solenoid actuator (Fig. 2). Laboratory experiments were performed at the Magnetics Testing Facility at APL, remote from other facilities, to allow nulling of background fields and calibrating of the gradient measurement. The algorithm also performs well in laboratory settings, obtaining residual errors of <5% when recovering the location and moment of the experimental solenoid actuator, providing confidence in the implementation of the tetrahedral correction for calibration in flight and during surface operations.

Ongoing Efforts: To anticipate different measurement profiles from VMx during surface operations, the tetrahedral correction algorithm is currently being adapted to identify multiple sources such as two solenoids, so that simultaneous thruster firing can be adjusted for in VML descent observations, for example. This is possible due to the overdetermination of the 6-dimensional parameter space for a single source. For an initial tetrahedral correction, the inversion quality of the final estimates can be assessed, and cost function and residual error thresholds set to determine when the single dipole approximation fails.

The tetrahedral correction algorithm is critical to the *Lunar Vertex* investigation, and these developments will improve magnetic gradiometry for future missions and instrument designs. The novel tetrahedral commercial sensor array employed by VML and VMR provides a complementary pathway for magnetic cleanliness efforts that allow for reduced mission costs while still providing science-grade magnetic observations.

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